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WEAK INTERSTELLAR LINES IN THE VISIBLE SPECTRUM OF ZETA OPHIUCHI

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ABSTRACT

Interstellar absorption lines in the spectrum of ζ Oph have been investigated using a synthesis technique to superpose 31 high-dispersion spectrograms in the wavelength region 3650–4340 Å. The minimum detectable equivalent width is approximately 0.25 mÅ. Lines which have been observed for the first time in the spectrum of this star are Ca I λ4226, Fe I λλ3720 and 3860, and K I λλ4044 and 4047. Using these data and assuming ionization equilibrium, a new evaluation of the electron density, hydrogen density, and elemental abundances is presented for the -15 km s^{-1} cloud. With the direct measurement of both the Ca I and Ca II column densities, the relative abundance computations are shown to be insensitive to the choice of radiation field and kinetic temperature.

Subject headings: interstellar matter — stars, individual

I. INTRODUCTION

The interstellar line spectrum of ζ Ophiuchi has been studied more thoroughly than that of any other star. Adams (1949) noted the presence of all then known interstellar absorption lines with the exception of those produced by Fe I and Ca I. Herbig (1968) has given a very thorough discussion of the physical conditions in the clouds where the lines are formed. He argued, based on 21-cm observations of the neutral hydrogen, and on optical and radio observations of the H II region close to ζ Oph, that the -15 km s^{-1} cloud is an H I region which is probably at least 15 pc from the star itself. He examined the physical conditions in the cloud using the equations of ionization equilibrium and assuming a normal (solar) sodium abundance. With these assumptions, an electron density of 0.4 cm^{-3} was computed, and a hydrogen density of about 700 cm^{-3} was estimated.

Hobbs (1973) has made accurate radial velocity and line profile measurements for several atomic lines and the strong CH$^+$ line λ4232. In comparing these observations, he noted a radial-velocity shift of 1.6 km s^{-1} between the CH$^+$ line and the single, sharp K I line λ7699 at -14.4 km s^{-1}. This difference may be interpreted to mean that the molecular lines and the atomic lines arise in different clouds or simply in different regions of the same cloud. In either case, it seems prudent to discuss the atomic ionization equilibrium independently of the molecular observations insofar as possible, and to avoid ascribing the same physical conditions to the atomic and molecular regions.

The *Copernicus* satellite has recently made far-ultraviolet observations of many previously unobserved atomic speeies (Morton *et al.* 1973). The results indicate that many elements, including carbon, are under-abundant relative to hydrogen. Most probably, the missing fractions are tied up in grains, but in light of Hobbs's (1973) observations referred to above, the possibility exists that the depletion factors may be different in the atomic and molecular regions. The *Copernicus* observations of molecular hydrogen (Spitzer *et al.* 1973) indicate that no more than 50 percent of the hydrogen in the line of sight is in the molecular form. Assuming that no large amount of hydrogen is locked in grains, it is apparent then that abundances computed from total line-of-sight atomic column densities will not be in error by more than a factor of 2.

In this paper, we present new ground-based observations of weak, atomic lines in the wavelength region 3650–4340 Å. The limiting sensitivity of the study corresponds to an equivalent width of approximately 0.25 mÅ. The Ca I λ4226 measurement permits an accurate determination of the electron density in the -15 km s^{-1} cloud (§ IV*e*) which is independent of any assumptions of normal abundance. The electron density is then used to compute elemental abundances (§ IV*c*) which are largely independent of the assumed radiation field. These abundances are finally compared with the solar abundances of Withbroe (1971) and the *Copernicus* satellite results (Morton *et al.* 1973).

II. OBSERVATIONS AND DATA REDUCTION

A total of 31 spectrograms of ζ Oph in the wavelength region 3650–4340 Å were obtained with the coudé spectrograph of the Lick Observatory 120-inch (3-m) telescope in 1968–1969. The dispersion, using the 160-inch (4-m) camera, was 1.3 Å mm^{-1}, and the resolution with a projected full slit width at half-maximum (FWHM) of 35 μ was $\lambda/\Delta\lambda = 100{,}000$. The average exposure time was 45 minutes, and the spectra were widened to about 5 mm.

The densitometry was carried out at the Goddard Institute for Space Studies using a D. W. Mann model

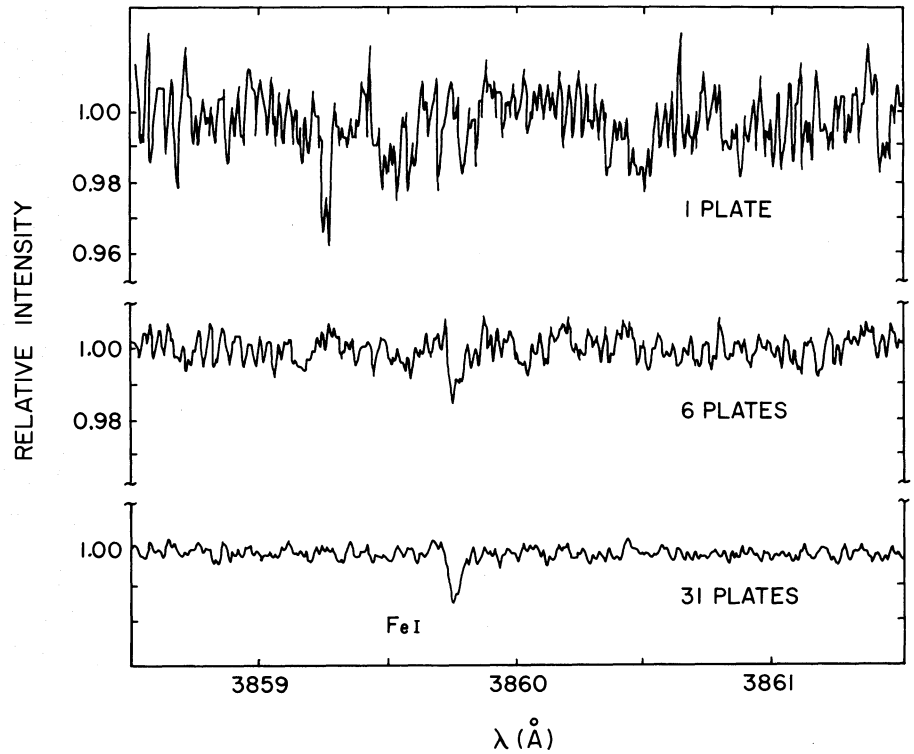

FIG. 1.—The increase in sensitivity resulting from the synthesis technique. The region near Fe I λ3860 in ζ Oph is shown for a single good plate and for spectra synthesized from 6 and 31 plates. The equivalent width of the line is 1 mÅ.

1140 microdensitometer with a scan slit projected FWHM of 10 μ. The output from the densitometer photomultiplier tube was digitized and recorded on magnetic tape together with the comparator screw position every 4 μ along the plate. Subsequent processing was entirely digital. For each spectrogram, the wavelength and intensity calibrations were carried out in the usual manner; the final product was a digital record of intensity as a function of wavelength. The accuracy of the wavelength calibrations was found to be better than 0.005 Å (0.4 km s^{-1} at 4000 Å) for all plates. Agreement between our equivalent widths and those measured by other observers is better than 10 percent, indicating that the usual accuracy for photographic intensity calibrations was achieved.

The 31 spectrograms were then combined to produce what we call the synthesized spectrum. The synthesis was accomplished by averaging the intensities at each wavelength using a weighting factor for each spectrum inversely proportional to the average mean-square noise. The resulting spectrum is the equivalent of a single 24-hour exposure. The dramatic improvement in signal-to-noise ratio is illustrated in figure 1, which shows the region near Fe I λ3860. The equivalent width of this new line is only 1 mÅ—about one-third the minimum detectable on a single high-quality plate.

III. RESULTS

The atomic absorption-line profiles found in the synthesized spectrum are shown in figure 2. Five of the seven atomic lines are the first such detections in the spectrum of ζ Oph: Ca I λ4226, Fe I λλ3720 and 3860, and K I λλ4044 and 4047. (The molecular lines will not be discussed here. The results may be found in previous publications: Bortolot, Clauser, and Thaddeus 1969; Bortolot and Thaddeus 1969; Thaddeus 1972.) The equivalent widths and heliocentric radial velocities of all the atomic lines are given in table 1, which also includes f-values and equivalent widths and velocities obtained by Herbig (1968). With the exception of Na I and Ti II (Herbig 1968) and Li I (Traub and Carleton 1973), absorption lines due to other atomic species are not known in the visible spectrum of ζ Oph.

All the lines in table 1, except those of Ca II at -15 km s^{-1}, are unsaturated, and the column density can be calculated from the usual relation

$$N = \frac{mc^2 W}{\pi e^2 \lambda^2 f} = \frac{1.13 \times 10^{20} W}{\lambda^2 f} \quad \text{cm}^{-2},$$

where W and λ are measured in angstroms. For Ca II, the doublet ratio method (Münch 1968) may be used. From our doublet ratio of 1.69, we obtain a column density of 4.8×10^{11} cm^{-2} and a Doppler width of 1.9 km s^{-1}. All of the column densities for the -15 km s^{-1} cloud are shown in table 2.

IV. IONIZATION EQUILIBRIUM

Our detection of Ca I λ4226 in the -15 km s^{-1} cloud permits a direct calculation of the ionization equilibrium and the electron density.

TABLE 1

INTERSTELLAR ATOMIC LINES IN ζ OPHIUCHI IN THE REGION 3650–4340 Å

Rest Wavelength* (Å)	Atom or Molecule	f-Value†	This Work W (mÅ)	This Work v‡ (km s⁻¹)	Herbig W (mÅ)	Herbig v‡ (km s⁻¹)
3719.935	Fe I	0.041[c]	1.9	−14.9	< 3.	...
3859.913	Fe I	0.023[d]	1.0	−15.0	< 3.	...
3933.664	Ca II	0.69	34.8	−15.1	34.2	−15.0
			9.8	−29.1	10.1	−29.0
3944.018[a]	Al I	0.115	< 0.26		< 3.	...
3968.470	Ca II	0.344	20.6	−14.8	21.3	−14.2
			4.7	−28.8	5.4	−28.0
4044.145[b]	K I	0.0061	0.8	−15.3	< 3.	...
4047.213	K I	0.0031	0.3	−15.0	< 3.	...
4226.728	Ca I	1.75	1.3	−15.8	< 3.	...

* All rest wavelengths are from Herbig (1968) except where noted. [a] Burgess *et al.* (1960). [b] Moore (1945).

† All atomic *f*-values are from Wiese *et al.* (1969) except as noted. [c] Bridges and Wiese (1970). [d] Corliss and Bozman (1962) scaled to the results of Bridges and Wiese (1970).

‡ Heliocentric velocity of line centroid.

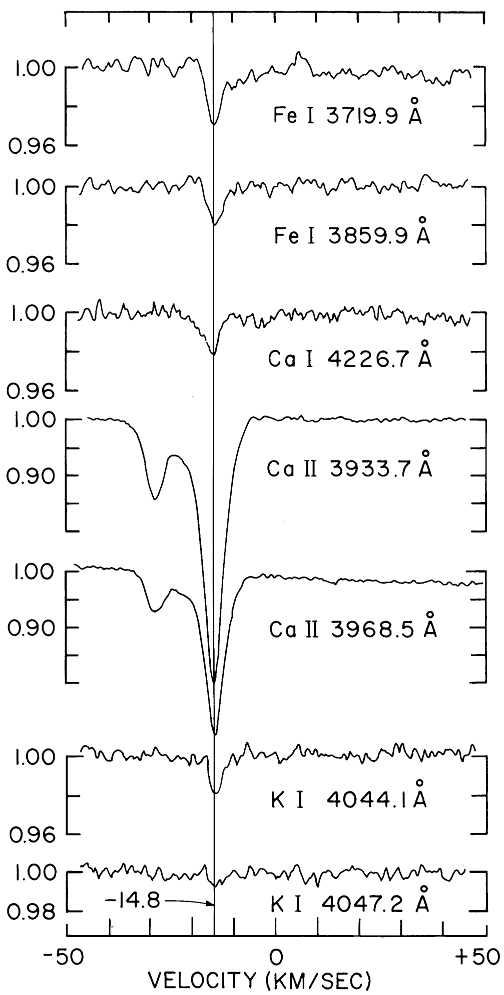

FIG. 2.—The atomic line profiles observed in the −15 km s⁻¹ cloud in the direction of ζ Oph plotted versus heliocentric velocity.

TABLE 2

ATOMIC COLUMN DENSITIES (−15 km s⁻¹ cloud)

Atom	λ (Å)	N (cm⁻² × 10⁻¹¹)
Fe I......	3719.935	3.8
	3859.913	3.3
Ca I......	4226.728	0.047
Ca II.....	3933.664	
	3968.470	4.8
K I.......	4044.145	9.1
	4047.213	6.8
Al I......	3944.018	< 0.16

The usual equation of ionization equilibrium is

$$\frac{n(X_{r+1})n_e}{n(X_r)} = \frac{\Gamma_r}{\alpha_r}, \tag{1}$$

where r is the stage of ionization, the n's are number densities (cm^{-3}), n_e is the electron density, Γ_r is the photoionization rate of atoms in the rth stage of ionization, and α_r is the total recombination rate to the rth stage of ionization. (The subscript r will be dropped from Γ and α hereafter.) The photoionization rate is

$$\Gamma = 10^{-8}h^{-1}\int_0^{\lambda_0} a_\lambda u_\lambda \lambda d\lambda\,, \tag{2}$$

where λ is in angstroms, λ_0 is the ionization threshold, a_λ is the photoionization cross-section (cm^2 atom^{-1}), and u_λ is the radiation density (ergs cm^{-3} Å^{-1}). From equations (1) and (2) and the observed column-density ratio Ca II/Ca I, we can compute n_e as a function of the radiation field; knowing the electron density, we can then compute abundances of atoms whose neutral form is observed, provided that their photoionization cross-sections and recombination rates are known. In order to proceed with this program, we must first decide on the ionization cross-sections and recombination rates to be used, and also choose a radiation field from among those available in the literature.

a) *Atomic Data*

For Ca I we adopt the relative photoelectric cross-sections of Newsom (1966) placed on an absolute scale a factor of 2.2 higher as determined by McIlrath and Sandeman (1972). The cross-sections of Hudson and Carter (1965, 1967) are used for K I and Na I, respectively. We use the recent theoretical Fe I cross-sections of Kelly and Ron (1971) and the new measurements of Kohl and Parkinson (1973) for the cross-sections of Al I. The recombination coefficients for Ca II, Na II, and K II are taken from Seaton (1951) while that of Al II is from Burgess, Field, and Michie (1960). The assumed electron temperature is 100° K. The recombination coefficient of Fe II is not known, but we adopt a value 0.6×10^{-11} cm^3 s^{-1}, comparable to that of other atoms.

It should be noted that recent measurements of photoionization cross-sections using new techniques for optical path-length determinations have shown that older absolute scales can be in error by as much as a factor of 3. These modern determinations are available for Ca I and Al I but not for Na I, K I, or Fe I. It is possible, therefore, that future laboratory work could make a substantial difference in the results presented here.

b) *Radiation Field*

The radiation field is somewhat uncertain. Recent calculations of the general galactic field (Habing 1968; Witt and Johnson 1973) disagree by a factor of 2 at some wavelengths. Furthermore, the distance of the -15 km s^{-1} cloud from ζ Oph is not known, and so the stellar contribution to the ionizing field is difficult to assess. To try to account for these uncertainties, we have calculated the ionization rates for two cases: a high radiation field where ζ Oph is assumed to be 15 pc from the absorbing matter, and a low field where ζ Oph is assumed far away. The ζ Oph radiation field is taken from the B0 V line-blanketed model of Hickok and Morton (1968), and the galactic radiation field used is the "average" field given by Habing (1968) in his table 8. Extinction is accounted for by assuming that the radiation field sees an average $E_{B-V} = 0.14$, which is one-half the reddening measured for ζ Oph. A grain albedo with a wavelength dependence given by Witt and Lillie (1972) is also included by multiplying the radiation field by a factor

$$[a_\lambda - (1 - a_\lambda)\,\mathrm{dex}\,(0.4A_\lambda)]^{-1}\,,$$

where a_λ and A_λ are the wavelength-dependent albedo and extinction, respectively. The resulting fields differ from each other by a factor of 3–5 over the wavelength region 912–2500 Å. This range of radiation density is useful because it brackets many of the other assumptions that might be considered including the radiation field of Witt and Johnson (1973), various assumptions about the average extinction seen by the atoms in the cloud, and various reasonable distances of ζ Oph from the cloud. The ionization rates calculated for the high-field and low-field cases are given in table 3 along with the corresponding recombination rates.

TABLE 3

ATOMIC PHOTOIONIZATION AND RECOMBINATION RATES

Atom	Γ ($\times 10^{11}$) s^{-1} High Field	Γ ($\times 10^{11}$) s^{-1} Low Field	α($\times 10^{11}$) cm^3 s^{-1}, T = 100° K
Na I......	3.96	0.93	0.59[a]
Al I......	385	138	0.85[b]
K I......	10.4	2.62	0.56[a]
Ca I......	73.9	21.1	0.60[a]
Fe I......	44.2	9.6	0.60[c]

[a] Seaton (1951). [b] Burgess *et al.* (1960). [c] Assumed.

c) *Electron Density*

The electron density can be computed from equation (1) using the Ca I and Ca II column densities from table 2 and the appropriate photoionization and recombination rates from table 3. For the low-radiation-field case, we obtain $n_e = 0.35$ cm^{-3}; for the high-field case, $n_e = 1.21$ cm^{-3}. This range of values for n_e is valid only if both the Ca I and Ca II lines are formed in the same H I region. The arguments for the region being an H I region have been thoroughly presented by Herbig (1968) and will not be repeated here. Herbig also argued that contributions from a tenuous medium or the H II region surrounding ζ Oph could not affect the column densities by more than a factor of 2. This reasoning is further strengthened by the high-resolution observations of Hobbs (1973) which show that the atomic species Ca II, Na I, and K I are heavily concentrated in a single component at a velocity of -14.4 km s^{-1}.

d) *Hydrogen Density*

If the conventional approximation for H I regions is used, the electron density is directly proportional to the hydrogen density, i.e., $n_e = 5 \times 10^{-4} n_{\mathrm{H}}$. This relation assumes that the free electrons are produced by the ionization of the readily ionized, most abundant, atomic species, C, Si, S, Fe, Mg. Applying this reasoning, we find a hydrogen density in the range 700–2400 cm^{-3}. Also, the ratio of the column density of electrons to the column density of hydrogen can be obtained directly from *Copernicus* observations of the ionized species (Morton *et al.* 1973); this ratio ranges between 6×10^{-5} and 8×10^{-4}. The higher value agrees with the conventional one used above. However, if there is substantial depletion of the elements and the lower value is correct, then the hydrogen density is in the range 5800–20,000 cm^{-3}. These densities are much higher than those normally considered for such H I regions. As pointed out recently by White (1973), this situation tends to support the conjecture that partial ionization of the hydrogen is taking place. With the maximum ionization rate of Spitzer and

Tomasko (1968), $\zeta = 10^{-15}\ \mathrm{s^{-1}}$, the maximum hydrogen densities computed above are reduced to the range 450–4500 $\mathrm{cm^{-3}}$. However, it has been pointed out that *Copernicus* results for N III and C III appear to rule out such a large ionization rate due either to cosmic rays or to soft X-rays (Mészáros 1973).[1]

e) *Elemental Abundances*

The observed Ca I/Ca II ratio presented here also permits us to calculate abundances for several elements. Substituting the electron density as a function of the column-density ratio, Ca I/Ca II, into equation (1), we have

$$\frac{N_{X\,\mathrm{II}}}{N_{X\,\mathrm{I}}} = \frac{\Gamma_X}{\alpha_X}\frac{\alpha_{\mathrm{Ca}}}{\Gamma_{\mathrm{Ca}}}\frac{N_{\mathrm{Ca\,II}}}{N_{\mathrm{Ca\,I}}}\,.$$

In general, although the neutral state is observed, the ionized state dominates for the elements of concern here, so that

$$N_X = N_{X\,\mathrm{I}} + N_{X\,\mathrm{II}} \simeq N_{X\,\mathrm{II}}$$
$$= \frac{\Gamma_X}{\Gamma_{\mathrm{Ca}}}\frac{\alpha_{\mathrm{Ca}}}{\alpha_X}\frac{N_{\mathrm{Ca\,II}}}{N_{\mathrm{Ca\,I}}}N_{X\,\mathrm{I}}\,. \qquad (3)$$

The interesting feature of equation (3) is that N_X depends only on the ratio $\Gamma_X/\Gamma_{\mathrm{Ca}}$ and $\alpha_X/\alpha_{\mathrm{Ca}}$, so that the computed abundances are only weakly dependent on the assumed radiation field and temperatures.

Abundances relative to hydrogen can be obtained by using the observed H I column density of 4×10^{20} atoms $\mathrm{cm^{-2}}$. The *Copernicus* results (Spitzer *et al.* 1973) show that the inclusion of molecular hydrogen cannot change these relative abundances by more than a factor of 2. Furthermore, Hobbs (1973) has shown that at least the CH^+ molecule appears at a radial velocity shifted 2 $\mathrm{km\ s^{-1}}$ away from the principal atomic lines. It is possible, therefore, that all of the molecules are in a different cloud, and we will omit consideration of the molecular hydrogen from the following discussion.

i) *Sodium*

The Na I column density was not measured in our work, and we take instead the value obtained by Herbig (1968) of $4.9 \times 10^{13}\ \mathrm{cm^{-2}}$. Applying equation (3), we find a total Na column density for the low- and high-field cases of $2.2 \times 10^{14}\ \mathrm{cm^{-2}}$ and $2.7 \times 10^{14}\ \mathrm{cm^{-2}}$, respectively. This result yields an abundance relative to hydrogen of 0.5–0.7 $\times 10^{-6}$, a factor of 2–3 lower than the solar value of 1.7×10^{-6} given by Withbroe (1971).

ii) *Potassium*

The computed total K column density is in the range 1.1–1.2 $\times 10^{13}\ \mathrm{cm^{-2}}$. The abundance relative to hydrogen is then 2.8–3.0 $\times 10^{-8}$, again slightly below the solar value of 1.1×10^{-7}.

iii) *Calcium*

The Ca I and Ca II column densities have both been measured leaving only that for Ca III to be computed. The photoionization threshold for Ca II is at 1049 Å. If we adhere to our assertion that the region contains mostly neutral hydrogen so that no radiation exists below 912 Å, then very little Ca III can be present; using the photoionization cross-section for Ca II calculated by Burgess and Seaton (1960) and the recombination rate of Seaton (1951), we find that less than 20 percent of the Ca can be in Ca III. Therefore, the Ca column density is essentially given by the Ca II value of $4.8 \times 10^{11}\ \mathrm{cm^{-2}}$. The abundance relative to hydrogen is then 1.2×10^{-9}—the well-known result that interstellar Ca is underabundant in the spectrum of ζ Oph by about a factor of 2000.

iv) *Aluminum*

From the upper limit in table 2, the computed total Al column density is found to be less than 6.0–7.1 $\times 10^{12}\ \mathrm{cm^{-2}}$. The abundance relative to hydrogen is less than 1.5–1.8 $\times 10^{-8}$. This result shows that Al is underabundant by at least a factor of 140 when compared with the solar value of 2.5×10^{-6} (Withbroe 1971). The *Copernicus* satellite's inability to detect Al II and Al III is consistent with the depletion of Al found here. However, the satellite spectrometer's low sensitivity at the appropriate wavelengths does not place as severe a constraint on the Al abundance.

The observed Al depletion is an order of magnitude greater than the Mg depletion observed by *Copernicus*, but it is not much greater than the upper range of the observed depletion of Fe.

v) *Iron*

The computed total Fe column density is 1.5–2.1 $\times 10^{13}\ \mathrm{cm^{-2}}$. The abundance relative to hydrogen is 3.9–5.3 $\times 10^{-8}$, which is about a factor of 500 less than the normal solar abundance. This result is about a factor of 5 beyond the upper end of the range of depletion factors allowed by the *Copernicus* observations (Morton *et al.* 1973). This disagreement may indicate that some revisions are required in the calculated photoionization cross-sections of Kelly and Ron (1971) which were used in our computations.

The total column densities, abundances relative to

[1] An anonymous referee has pointed out that these high densities imply a pressure in the cloud well in excess of that for the general interstellar medium. For a hydrogen density of 1000 $\mathrm{cm^{-3}}$ and a temperature of 100° K, $n_{\mathrm{H}}T$ is 10^5 ° K $\mathrm{cm^{-3}}$, while in the intercloud medium $n_{\mathrm{H}}T$ is on the order of 10^3 ° K $\mathrm{cm^{-3}}$. This situation is improved somewhat if the kinetic temperature is dropped to about 50° K in the cloud as suggested by the lower rotational-level populations of H_2 (Spitzer *et al.* 1973). In the case where no hydrogen is ionized, n_{H} is proportional to n_e, which in turn is proportional to α^{-1}, the Ca II recombination rate. The recombination rate has a $T^{-0.7}$ temperature dependence so that $n_{\mathrm{H}}T$ varies as $T^{1.7}$. Therefore, reducing the temperature by a factor of 2 reduces the electron and hydrogen densities by a factor of 1.6, and the pressure by a factor of 3.2. To come closer still to pressure equilibrium in the interstellar medium, the hydrogen density in the cloud must be reduced further. It is noteworthy, however, that both the low hydrogen ionization rate and the depletion of trace elements implied by *Copernicus* results point to a high hydrogen density.

TABLE 4

ELEMENTAL ABUNDANCES IN ζ OPHIUCHI

Element	Total Column Density* N (cm^{-2})	Relative Abundance* N/N_H	Depletion Factor $(N/N_H)_\odot/(N/N_H)$
Na......	$2.2–2.7 \times 10^{14}$	$0.5–0.7 \times 10^{-6}$	2.8
K.......	$1.1–1.2 \times 10^{13}$	$2.8–3.0 \times 10^{-8}$	3.8
Ca......	4.8×10^{11}	1.2×10^{-9}	1800
Al.......	$< 6.0–7.1 \times 10^{12}$	$< 1.5–1.8 \times 10^{-8}$	$>$ 140
Fe.......	$1.5–2.1 \times 10^{13}$	$3.9–5.3 \times 10^{-8}$	540

* The two values given correspond to the low and high radiation fields discussed in the text.

hydrogen, and depletion factors relative to Withbroe's solar abundances (1971) are summarized in table 4.

V. SUMMARY

The observations described here indicate that rather precise information on dense H I regions can be obtained by high-sensitivity, ground-based spectral observations. In particular, observations of the Ca I/Ca II ratio directly yield the electron density, which in turn yields quite accurate abundances for a number of elements. The numerical results obtained for the -15 km s^{-1} cloud in the direction of ζ Oph can be summarized as follows:

1. The electron density is in the range 0.35–1.2 cm^{-3}.

2. The hydrogen density may be as high as 5800–20,000 cm^{-3} if no ionization of the hydrogen is taking place. However, if the hydrogen is partially ionized, the density could be less than 450 cm^{-3}.

3. Abundances relative to hydrogen can be determined accurately with only a slight dependence on the choice of the radiation field. Sodium and potassium are slightly underabundant by a factor of 3, while Ca, Al, and Fe appear to be depleted by factors ranging from 140 to 1800. All elements, therefore, appear to be locked-up to some extent in the interstellar grains. However, in the case of Na and K, better measurements of the absolute photoionization cross-sections are probably needed to confirm this conclusion.

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REFERENCES

Adams, W. S. 1949, *Ap. J.*, **109**, 354.
Bortolot, V. J., Clauser, J. F., and Thaddeus, P. 1969, *Phys. Rev. Letters*, **22**, 307.
Bortolot, V. J., and Thaddeus, P. 1969, *Ap. J. (Letters)*, **155**, L17.
Bridges, J. M., and Wiese, W. L. 1970, *Ap. J. (Letters)*, **161**, L71.
Burgess, A., Field, G. B., and Michie, R. W. 1960, *Ap. J.*, **131**, 529.
Burgess, A., and Seaton, M. J. 1960, *M.N.R.A.S.*, **120**, 121.
Corliss, C. H., and Bozman, W. R. 1962, *NBS Monog.*, No. 53.
Habing, H. J. 1968, *Bull. Astr. Inst. Netherlands*, **19**, 421.
Herbig, G. H. 1968, *Zs. f. Ap.*, **68**, 243.
Hickok, F. R., and Morton, D. C. 1968, *Ap. J.*, **152**, 203.
Hobbs, L. M. 1973, *Ap. J. (Letters)*, **180**, L79.
Hudson, R. D., and Carter, V. L. 1965, *Phys. Rev.*, **139**, A1429.
———. 1967, *J. Opt. Soc. Am.*, **57**, 651.
Kelly, H., and Ron, A. 1971, *Phys. Rev. Letters*, **26**, 22.
Kohl, J. L., and Parkinson, W. H. 1973, *Ap. J.*, **184**, 641.
McIlrath, T. J., and Sandeman, R. J. 1972, *J. Phys. B: Atom. Molec. Phys.*, **5**, L217.
Mészáros, P. 1973, *Ap. J. (Letters)*, **185**, L41.
Moore, C. E. 1945, *A Multiplet Table of Astrophysical Interest* (Princeton: Princeton University Observatory).
Morton, D. C., Drake, J. F., Jenkins, E. B., Rogerson, J. B., Spitzer, L., and York, D. G. 1973, *Ap. J. (Letters)*, **181**, L103.
Münch, G. 1968, in *Stars and Stellar Systems*, Vol. **7**, ed. E. M. Middlehurst and L. H. Aller (Chicago: University of Chicago Press), p. 365.
Newsom, G. H. 1966, *Proc. Phys. Soc.*, **87**, 975.
Seaton, M. J. 1951, *M.N.R.A.S.*, **111**, 368.
Spitzer, L., Drake, J. F., Jenkins, E. B., Morton, D. C., Rogerson, J. B., and York, D. G. 1973, *Ap. J. (Letters)*, **181**, L116.
Spitzer, L., and Tomasko, M. G. 1968, *Ap. J.*, **152**, 971.
Thaddeus, P. 1972, in *Ann. Rev. Astr. and Ap.*, Vol. **10**.
Traub, W. A., and Carleton, N. P. 1973, *Ap. J. (Letters)*, **184**, L11.
White, R. E. 1973, *Ap. J.*, **183**, 81.
Wiese, W. L., Smith, M. W., and Miles, B. M. 1969, *Atomic Transition Probabilities*, Vol. **2**, *Sodium through Calcium*, NSRDS-NBS 22 (Washington: U.S. Government Printing Office).
Withbroe, G. L. 1971, *The Menzel Symposium* (NBS Special Pub. 353), ed. K. B. Gebbie (Washington: U.S. Government Printing Office).
Witt, A. N., and Johnson, M. W. 1973, *Ap. J.*, **181**, 363.
Witt, A. N., and Lillie, C. F. 1972, *The Scientific Results from the Orbiting Astronomical Observatory (OAO-2)* (NASA SP-310), p. 199.

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